

Prediction of Draping Behavior of Woven Fabrics over Double-Curvature Moulds Using Finite Element Techniques

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(Abstract) The fabrication of textile reinforced polymer composites requires the pre-forming of textiles over open, or within closed moulds before the introduction of the resin. This study is therefore concerned with the draping behavior of jute and glass fibres of various areal densities over double curvature moulds. Experimental investigation of the draping behavior was performed over a specially designed mould comprising different geometries of fillets and sharp edges. Simulation of the deformation behavior using PamForm2G application revealed similar results. Large shear deformations are found around large curves and acute angles. The interaction of geometries further forces woven fabrics to undergo severe shear deformations often leading to the creation of wrinkles.

Keywords: Fabrics, Textiles; Computational Modeling; Finite Elements; Draping Behavior

1. INTRODUCTION

The use of fibre reinforced composites has gained a considerable amount of recognition within the last decades. The variations in fibre types (glass, carbon, natural, etc.) as well as the variations in shape and dimensions have lead to the development of a vast basis for selection allowing for the flexible tailoring of the end product properties. Within this scope, however, the use of continuous dry textiles, especially in form of woven fabrics in various orientation patterns plays a vital role in the field of polymer composite.

A woven fabric consists of interlaced warp and weft yarns, where the warp is the 0° direction as the fabric comes off the roll, while the weft is the 90° fibre direction. Typically, woven fabrics are more deformable than stitched materials. However, the specific weave pattern affects their deformability characteristics, as well as the handle ability and structural properties of the woven fabric. [1, 2]

Since all processing techniques of fibre reinforced composites are related to moulding operations, the deformation behavior of the textiles over an open mould or within a closed mould is vital for the guarantee of the aesthetics and performance of the end product..

The deformation behavior of textiles is known as "drape" and is considered as an important mechanical property that affects the functionality of fabrics [3, 4]. The definition of drape has been largely discussed in the literature. Cusack [5] reported that the description of draping may be either aesthetic or objective. Chu et al. [6] described the drapability as the "property of textile materials which allows a fabric to orient

itself into graceful folds or pleats when acted upon by the force of gravity", hence portraying a qualitative term in such a way that, a fabric is said to have good draping qualities when the configuration is pleasing to the eye [6]. In a later attempt, drape was identified as "the deformation of the fabric produced by gravity when only part of it is directly supported" [5, 7]. Recently, draping has been defined as "the extent to which a fabric will deform when it is allowed to hang under its own weight" (BS 5058:1973; British Standard Institute, 1974b) [3, 4].

Fabrics may drape in various ways and shapes depending on fibre content and different physical, structural and mechanical properties of the fabric. In addition to the fabric properties, the amount of deformation it undergoes and the deformation mechanisms are strongly dependent on the geometry over which it drapes [3].

The materials considered in this study are thin textile composite reinforcements where the thickness is very small in relation to the warp and weft length. Consequently, the wrinkling risk is high and strongly increased by the fibrous nature of the reinforcement. Thin structures are subject to wrinkling as their bending stiffness (out-of-plane) is much lower than the in-plane. Literature [8] reports that for a given thickness, the bending stiffness of a woven fabric is lower than that of a plate made of the same continuous material (i.e. in sheet form) because of the possible sliding between its constituting fibres. The ability to develop wrinkles is thus very high for textile materials. In this respect, prediction of these wrinkles depending on the forming parameters is a key point especially in the useful parts of the mechanical component.

Table 1. Woven fabric properties

Material type	Areal density (g/m ²)	Cover factor	Tensile modulus (MPa)	Shear lock angle	Bending rigidity (mg.cm)	Bending length (mm)
NF 192	192	10.7	13.4	54	1455	41.9
NF 241	241	11.5	20.9	51.5	2091	45.9
NF 250	250	13.3	25.5	47	2818	48.6
NF 272	272	17.0	27.5	42.5	3818	52.7
NF 616	616	8.1	2.5	41	1727	31.1
GF 276	276	13.0	240	53.5	1091	35.1
GF 611	611	20.4	260	52	22500	68.9

The purpose of this work is to model the draping behavior of woven fabrics over double curvatures to predict their deformation characteristics in any of the composite manufacturing techniques.

2. MATERIALS AND METHODS

2.1. Materials

Five commercially available jute woven fabrics were supplied by El-Manasra, Egypt. For comparison, two further glass fibre woven fabrics were further supplied by HP Textiles, Germany. The fabrics are all of the plain weave type and show measured variations in density, weave dimensions and mechanical properties, as listed in Table 1. Details related to the measurement of mechanical and physical properties are reported by Abdin [9].

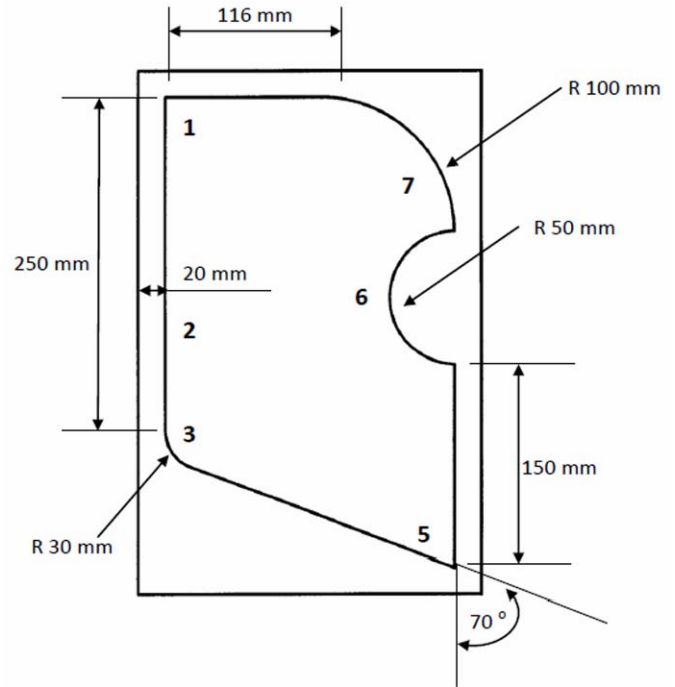
2.2. Double Curvature Draping

A fabric sample of $550 \times 450 \text{ mm}^2$ is placed over a positive mould, with shape and dimensions as illustrated in Figure 1. The test rig comprises the positive mould half, which is fixed onto a sliding table guided by four shafts that are in turn pinned to the rig's base, as can be depicted from Figure 2. The guide shafts allow only vertical movement of the positive mould, by means of a hydraulic piston.

The sliding table is gradually elevated until the fabric surface reaches the top of the fixed negative mould. The top surface of the negative mould is equipped with a transparent PMMA plate, to allow the observation of fabric draping behavior. A camera is mounted above the complete setup for image acquisition purposes.

A $10 \times 10 \text{ mm}^2$ grid mesh is manually drawn on each sample before the experiment to be able to fully and accurately characterize the deformation pattern upon draping.

In the present study only a two dimensional system is considered, focusing on the bottom of the mould where typical wrinkling defects occur, thus allowing the characterization of the in-plane deformation of reinforcement textiles.

**Figure 1.** Double curvature mould

2.3. Numerical Techniques

Making use of the PamForm software, PamForm2G is a calculation code that uses the Finite Element (FE) method, where all the components of a calculation are shown as meshes, i.e. discrete representation of geometry [10]. For the present case, the material type 140 is applied. This type is generally used for composite materials simulation (laminate forming with single fibre layers), where its constituents are schematically illustrated in Figure 3 in terms of material law components, being: 1) the extensible reinforcing fibre component, 2) the matrix component, and 3) the parent sheet component. The latter component is merely a numerical fitting component used to overcome the strong numerical instabilities that occur due to the high anisotropic behavior of the materials typically modeled by Material Type 140. Three main objects are defined in the simulation, modelling negative mould, positive mould and fabric.

The attributes defined for the negative mould involve the rigid body object type (surface tool), where its cartesian kinematics are all locked to simulate the experimental setup where the negative mould remains at fixed position. A friction coefficient μ of 0.1 with the „blank“, i.e. the fabric, is assumed.

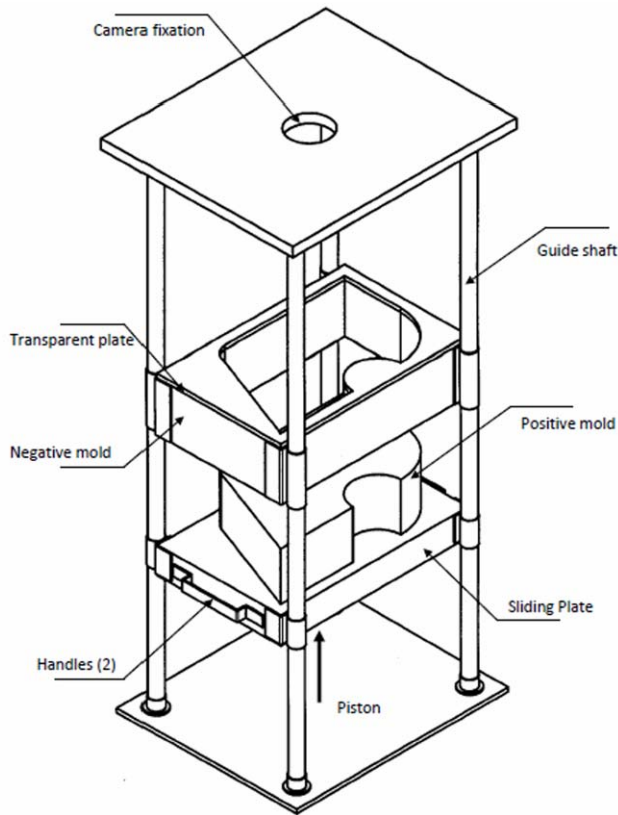


Figure 2. Test rig setup for the investigation of drape over double curvatures

The positive mould is similarly defined as a rigid body surface tool object where only translational motion in the z direction is permitted according to the velocity profile described in Figure 4. Again, a friction coefficient of 0.1 between mould and blank is assumed.

The blank attributes of the fabric to drape include „surface blank“, which is an object type typically used to define shell elements of blank sheets. Further properties of the fibre components are provided in terms of its tensile modulus, bending factor F_b , the out-of-plane shear factor F_s , the shear modulus G , and Poisson's ratio. The bending factor represents the fabric bending resistance. F_b values depend on the bending length c , as illustrated in Figure 5.

In contrast, for all fabrics under investigation, a "knock down" value for $F_s = 0.0001$ is applied, based on the fact that the deformation mechanism of fabrics is in-plane shear where the yarns are rotated until shear locking in a plane is achieved. Fabric out-of-plane shearing remains thus negligible.

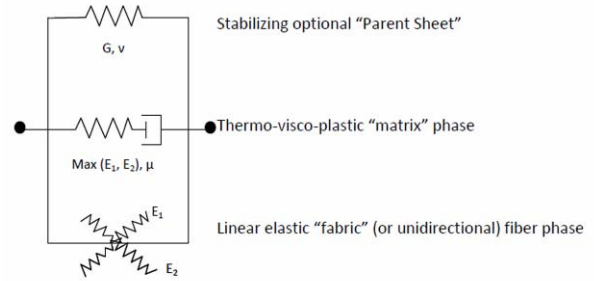


Figure 3. Schematic representation of PamForm Material 140 components

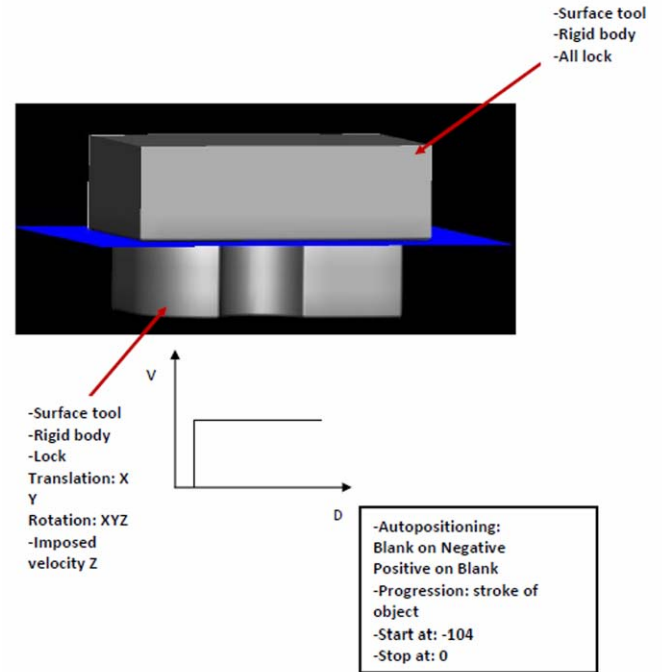


Figure 4. Simulation of experimental setup comprising mould and blank

The parent sheet is used for stabilizing the simulation. A Poisson's ratio of $\nu=0.2$ is adapted. The shear modulus is supplied in accordance with the advanced shear model approach, where the shear characteristics of the fabric are entered into the model in form of a continuous curve describing the shear modulus with respect to various shear angles. This allows a smooth and continuous description of the shear behavior over the complete course of deformation. A drawback, however, remains the complication of solution and the increase of computation time.

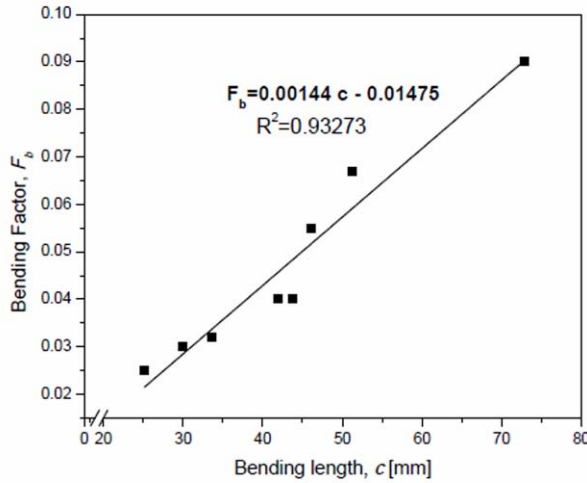


Figure 5. Bending factor plotted against bending length

Generally, the material input parameters can be summarized as in Tables 2, describing the fixed, fibre component variable, and parent sheet variable parameters. F_{bm} and F_{sm} denote the out-of-plane bending and shear factors of the matrix, respectively [10]. Trials have proven the reasonability of assuming $F_{bm} = F_b$, and $F_{sm} = F_s$, such that the imaginary matrix is assumed to have identical properties with those of the fabric, thus restricting simulation to dry fabric behaviour.

Figure 6 shows the draping output of some selected fabric types. Analyzing the grid deformation, it can be observed that the NF_241 fabric performs largest shear deformation in terms of shear. Shear deformation is found to deteriorate in the order of NF_241, NF_250 and further NF_272. These visual observations are comprehensible from the shear lock angle trends given in Table 1. Based on the low in-plane shear resistance of such fabrics, relative rotation between its weft and warp yarns is relatively easy. However, at some point the rotating tows contact each other, restricting further shear and leading to subsequent lock-up. As a result, the fabric is forced to bend in an orthogonal direction, where the bending stiffness of the fabric is considered lower than the increased in-plane shear. This phenomenon is then observed as wrinkling. Thus, low shear lock angles (42.5° for NF_272) denote high shear resistance, such that relative fibre locking of weft and warp yarns occurs at an early deformation stage. This difficulty in complying to mould shape due to poor shear properties is also demonstrated by the increased formation of wrinkles.

Further examination of the grid pattern shows that large shearing occurs at the 90° and 70° edge geometries. Larger deformation is observed at the area around the convex curvature, which is the source for most wrinkle initiation. However, largest shear deformations are seen at the 100 mm radius curvature. The reason therefore lies probably in the interactive effect of the neighboring 90° edge and convex curvature, being accentuated at the curvature. These large

Table 2. Summary of material input parameters

FIXED PARAMETERS							
Fs1		Fs2		μ		Fsm	
0.0001		0.0001		0.1		0.0001	
FIBRE COMPONENT VARIABLE PARAMETERS							
Fabric Type	Thickness	ρ	E_1	E_2	F_{b1}	F_{b2}	F_{bm}
NF_192	0.8507	2.26E-07	0.0162	0.0134	0.4	0.4	0.04
NF_241	0.72917	3.43E-07	0.0184	0.0288	0.04	0.04	0.04
NF_250	0.7021	3.44E-07	0.0248	0.0255	0.065	0.065	0.065
NF_272	0.74611	3.65E-07	0.0198	0.028	0.067	0.067	0.067
NF_616	1.8	3.4E-07	0.0022	0.0249	0.03	0.025	0.03
GF_267	0.382	6.67E-07	0.2509	0.227	0.032	0.032	0.032
GF_611	0.81	7.63E-07	0.2502	0.265	0.09	0.09	0.09
PARENT SHEET VARIABLE PARAMETERS							
Fabric Type		α_{lock}		G		G_{lock}	
NF_192		54		2.57E-05		3.71E-05	
NF_241		51.5		5.52E-05		6.33E-05	
NF_250		47		5.72E-05		9.6E-05	
NF_272		42.5		0.000102		0.000161	
NF_616		41		7.45E-05		0.000125	
GF_267		53.5		7.42E-05		8.52E-05	
GF_611		52		9.2E-05		0.000141	

Simulation is defined to start at an initial position, where all three objects (positive mould, negative mould and blank) are in contact, as illustrated in Figure 4. A stroke of the positive mould object is defined to end when the blank reaches the transparent top surface of the negative mould.

deformations are especially visible in the NF_272 fabric, where the fibre was clearly pulled away from the mould contour (un-gridded area at the).

3. RESULTS AND DISCUSSION

3.1. Double Curvature Draping

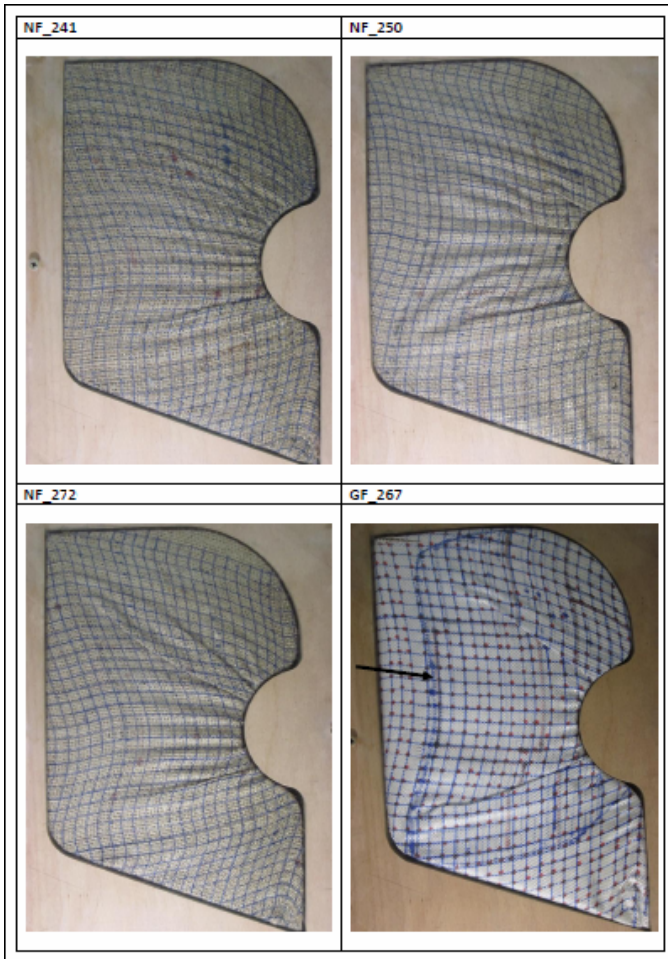


Figure 6. Digital images of various jute fibre fabrics draped over the double curvature mould

The deformation patterns exhibited by the low density GF_267 in terms of shear angles, are similar to those observed for the NF_241 fabric. This is to be expected, based on the shear lock angle properties of the fabrics (Table 1). However, excessive wrinkling in the GF_276 fabric is remarkable. This can be attributed to its low bending rigidity of 1091 mg.cm as listed in

Table 1. This, however, does not impair the fabric's favorable shear behavior. Instead, care must be taken during processing to provide sufficient straightening to the fabric by means of blank holders to prevent out-of-plane deformation [9].

Figure 6 also shows the extent to which the fabric near the straight edge had to be pulled to accommodate for the large shearing and wrinkling actions. The arrow indicates the initial straight edge position of the fabric. Observing the draping development also evidences that draping started at the straight edge, where the fabric was then further pulled by the opposing and neighboring curvatures.

The above observations reflect the importance of examination of in-plane shear behavior of fabrics, and its major influence on draping around double curved surfaces. Moreover, interaction between geometries strongly influences fabric draping behavior. This is in agreement with analysis performed by Hancock et al. [11] who investigated the draping behavior of fabric in asymmetric moulds and suggested that

draping patterns need to be modeled prior of manufacturing in order to achieve better efficiency of mould design due to possible complex interactions between mould curvatures. However, it can be generally stated that to avoid excessive wrinkling of fabric during moulding operations material as well as design aspects have to be taken into consideration. Fabrics of low areal density, high shear lock angles and low bending rigidity would tend to conform more easily to mould shape. Mould design should avoid excessive curvatures or acute angles, and geometrical changes are preferred at a safe distance apart from each other. Excessive wrinkling is expected to not only affect the aesthetics of the final product, but may also bring about problems of resin impregnation during resin infusion operations. Interfolded fabrics might not get sufficiently wetted, leading to dry interfaces of a layered structure, which affects the performance of the end product governed by the premature damage of the reinforcement and the intermittent nature of the matrix.

3.2. Numerical Simulation

Figure 7 shows the different stages of the simulation. Figure 8 further presents the simulation outputs for the various jute fibre fabrics under investigation. The output is based on plotting the intensity of shear angles. For comparison purposes, deformations implying shear angles greater than 15° are given one color code (magenta).

Simulation figures (Figure 8) are in very good agreement with experimental observations (Figure 6). Hence, simulation is able to well predict deformation and wrinkling patterns. Similar to experimental outcomes, fabrics with low shear resistance (e.g. NF_241) undergo high amounts of deformations resulting as can be depicted from the high shear angles (max shear angle of 56°). Such high values could only

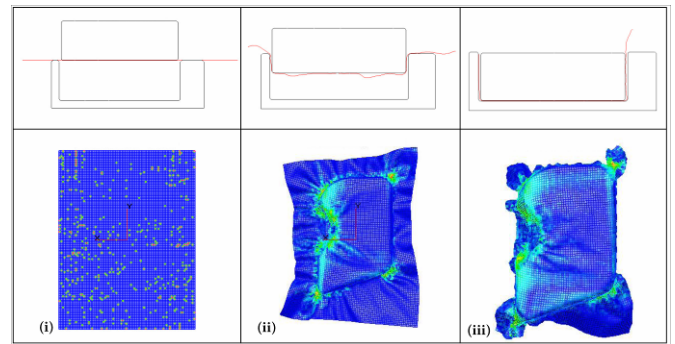


Figure 7. Stages of the simulation process: (i) at beginning, (ii) midway and (iii) end of draping

be attained based on the relatively high shear lock angle of this fabric, delaying fibre interlocking and herewith wrinkling.

conformity to mould shape. However, the bending properties of the fabrics also play a major role as reported by Abdin [9] who stated that extremely low bending resistance and ply thickness may be a main criterion for the creation of wrinkles.

4. CONCLUSIONS

Increased cover factor (implying increased areal density and fabric tightness) results in increased shear resistance, and hence poor draping qualities. In addition to shear behavior, out-of-plane bending properties additionally contribute to final draping. Thus, to avoid wrinkling of reinforcement fabrics in moulding operations, fabrics of low in-plane shear and high bending resistance are to be favored.

Whenever possible, acute angles and large edge curvatures should be avoided in mould design. The interaction of different mould geometries is also to be avoided. Simulation techniques for the optimization of mould design and material selection have been proven to be a successful tool.

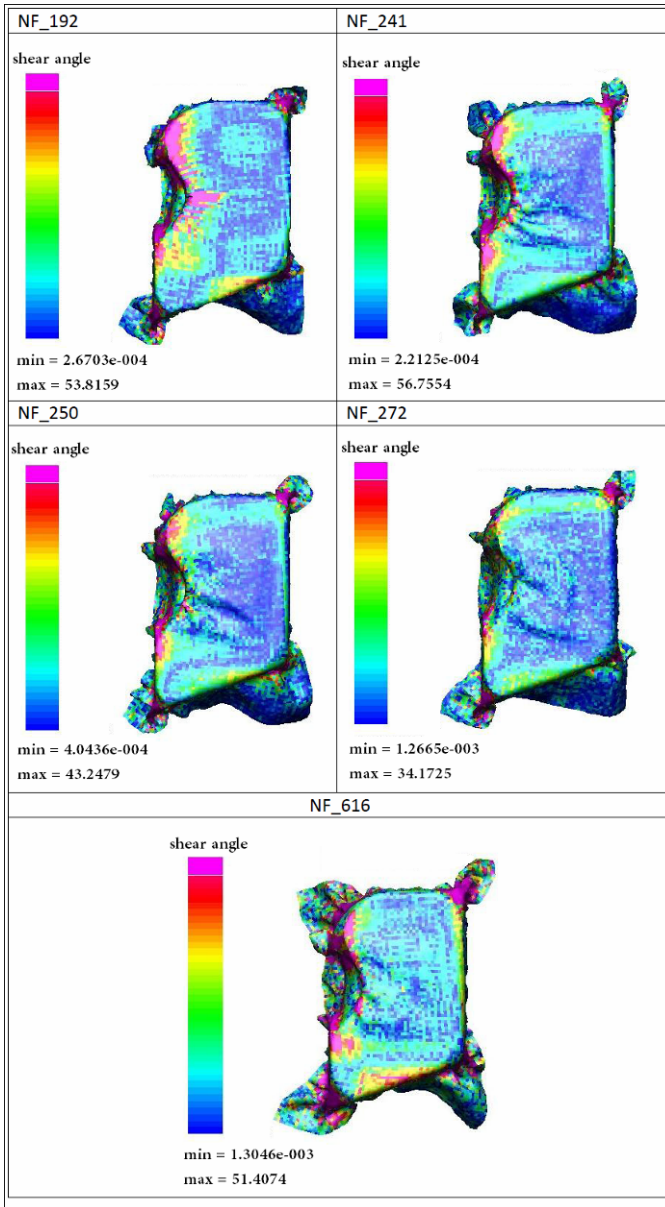


Figure 8. Simulation results for the various jute fibre fabrics under investigation

Further, in agreement with experimental observations, it is found that areas around the convex curve are subjected to highest shear deformations, exceeding the prescribed interlocking stage, and in turn leading to extreme wrinkling. Excessive shear deformation at points of geometry interactions can also be observed at the 90° and 70° edges which reach over in terms of increased shearing and promoted wrinkling near the convex curve area, as previously described in the experimental observations.

The simulation also well predicts the shear behavior exerted by the low density GF_276 fabric (**Figure 9**), which based on its very low shear resistance in addition to its low bending resistance, demonstrates large shear deformations near the straight edge, as seen by the large amount of wrinkles.

Hence, it must be noted that low shear resistance is not sufficient to ensure good draping behavior and acceptable

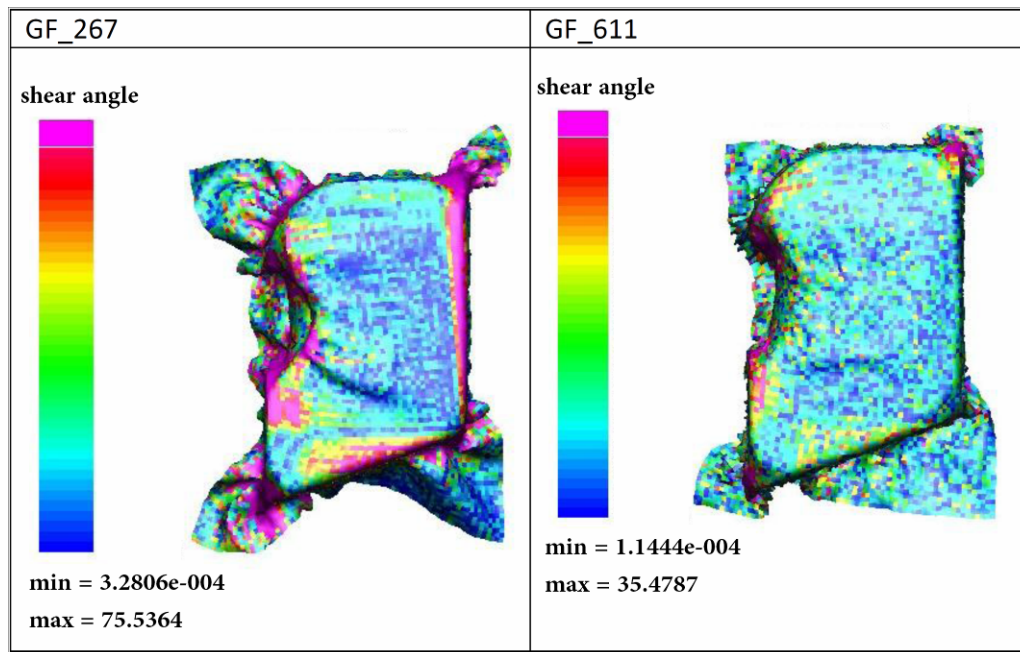


Figure 9. Simulation results for the glass fibre fabrics under investigation

5. ACKNOWLEDGEMENT

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